

THE WORLD OF CHEMISTRY

Program #22

THE AGE OF POLYMERS

Producer Frank Nesbitt

Air Script: October 31, 1988

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Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: Chemists at work,
fibers, car door, silk

NARRATOR (MUSIC under):
The alchemists of the Middle Ages tried
to turn base metal into gold. Today,
industrial chemists routinely turn oil and
natural gas into thousands of synthetic
polymers which redefine the way we
live. We have learned how to create
materials harder than steel, softer than
silk, and far less expensive than either.
What is the secret? How have we
created the age of polymers?

SUPER: THE AGE OF
POLYMERS

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH in office

ROALD HOFFMANN (SYNC/VO):
Stone Age, Bronze Age, Iron Age. The ages of man are defined by the materials that we use. What age are we living in today? This is the age of large factory-made synthetic molecules called polymers. Polymers are all around us, and they've replaced many of the materials that we normally use.

Factory shots, city street scenes

Are polymers, in fact, something new? No, they're not. Cotton, wool, wax have been with us since the beginning of civilization, and these, too, are large molecules. We call them biopolymers. And we certainly haven't been replaced. We are largely macromolecules and water.

RH in office

What is so special about polymers, natural or synthetic? And how have we learned to make these? Because, after all, the simple building blocks that nature provides us are small molecules, and these are quite complicated larger ones. It is only in this century that we have learned to tailor and control the properties of the molecules that we make.

MONTAGE: Water, clothing,
construction shots, food wrap,
car crash test, floor, ice rink,
football game, plastics on
assembly line, operating room,
chemists working in labs,
factory shots, oil dripping

NARRATOR (MUSIC and NAT
SOUND under):

In our daily lives, we are surrounded by materials that are totally new. Synthetic polymers clothe us, shelter us, protect our food, protect our bodies. We walk on polymers, we skate on polymers, we play football on polymers. The colors and sounds of everyday life are created and reproduced on synthetic polymers. Yesterday the word "plastic" meant cheap and inferior. Tomorrow, plastic may replace our bodily organs as they begin to wear out. How does modern chemistry create all these new materials and products? How can we get so much diversity from a common starting point? We are about to show you how thousands of small molecules are combined into giant macromolecules called polymers. You will see how one small molecule, ethylene, can become a building block for so many different polymers and products. Yet they, and ethylene, all have a common origin in crude oil or natural gas.

MONTAGE: Supertankers,
gas pipelines, oil well, crude
oil, refinery shots

NARRATOR (MUSIC and NAT
SOUND under):

Every day the world consumes another 5 billion liters of petroleum. Nations rise to prosperity or slide into poverty depending on fluctuations in the price of a barrel of crude oil. But without processing, crude oil straight from the ground is practically useless. Crude oil comes to the refinery as a complex mixture of gaseous, liquid, and solid hydrocarbons. The first step in refining the raw crude is called fractional distillation, and it takes place in these huge towers.

GRAPHIC: Fractional
distillation -- cut away
diagram of plant

NARRATOR (MUSIC and NAT
SOUND under):

Hot crude oil is fed in near the bottom of the tower, where it is heated again with steam. The column is cool at the top. Lighter hydrocarbons, those with fewer carbon atoms, boil at a lower temperature and rise to the top of the tower as gases. Heavier hydrocarbons, those with more carbon atoms, flow toward the bottom of the tower as liquids and solids. (cont.)

NARRATOR cont:

Nothing is wasted. At the very top of the tower are the gases, methane, ethane, propane, butane. Next comes gasoline and many important petrochemicals. Below that is the kerosene fraction for jet fuel. Then there is diesel oil and, at the bottom, lubricants and asphalt.

Oil refinery shots,
transporting oil,
city scenes

NARRATOR (NAT SOUND under):

At the end of this process, one barrel of crude oil leaves the refinery as a variety of important substances. But are these substances all equally useful? How do we get more of what we need the most? Crude oil does not yield enough gasoline or even ethylene through fractional distillation to meet our demands. Fortunately, both the heavier and lighter fractions can be subjected to further treatment, known as cracking.

Catalytic cracking towers

NARRATOR (MUSIC under):

These huge chambers are catalytic cracking towers. Here the heavier hydrocarbons are subjected to heat, pressure, and the action of a catalyst.

GRAPHIC: Cracking --
molecular level

NARRATOR (MUSIC under):
The heavy molecules crack into
fragments of lower molecular weight,
producing more hydrocarbons in the
gasoline range.

Oil refinery, balloon

NARRATOR (MUSIC and NAT
SOUND under):
By adjusting the quantity of material that
is handled in each of these processes, the
refinery can produce the commodities
that society needs the most. That's how
we get more ethylene. A fundamental
molecular building block of synthetic
polymer chemistry.

GRAPHIC: Polymerization
of ethylene

NARRATOR (MUSIC under):
This is the molecular geometry of
ethylene, 2 carbon atoms and 4
hydrogens. The ability of ethylene to
form polymers comes from the double
bond which joins the carbon atoms.
Ethylene is a monomer. Standing by
itself, it doesn't polymerize, until we add
an initiator, such as this organic
peroxide. The bond between the oxygen
atoms splits apart to form free radicals,
reactive particles with unpaired
electrons. The free radical quickly
combines with an ethylene molecule.
(cont.)

NARRATOR cont:

The product is also a free radical. It, too, reacts with an ethylene molecule. This is repeated many times and the chain grows. This sequence is called a free radical chain reaction. Eventually, we must stop the process or the polymer chain will be too long. The reaction ends when two chains link up.

MONTAGE: Train, factory shots, plastic wrap, asbestos suits, bowling, fuel tank, skating rink

NARRATOR (NAT SOUND under):

Imagine a freight train being assembled one box car at a time. Each car rolls down the hill and clamps onto the car ahead of it. Then along comes another car. And so it goes. Many cars become one train. Today, polyethylene is the world's most popular synthetic polymer. We manufacture 6 billion kilograms of it a year. It's a clear stretchy food wrap, or an impenetrable protective garment. It's a bowling pin, a fuel tank, a skating rink. Polyethylene has many different uses and many different properties. Series demonstrator, Dr. Donald Showalter.

DS in lab

DON SHOWALTER (SYNC):

Let's examine some of the material around us here. All of this stuff is polyethylene. Some of it bounces, some of it breaks. Some of it tears easily, some of it doesn't. Why do these common objects have such different properties?

SUPER: POLYETHYLENE

There are many different kinds of polyethylene. I'm going to show you three. Let's take this stuff. You may call it sandwich wrap. I call it low density polyethylene. It's very flexible. How about this bottle? I can crush it. I could probably even tear it, but it would take some hard work. It's made from high density polyethylene. The bottle might be tough, but the cap is even tougher. It's made from cross-linked polyethylene. How can one substance, one polymer, have so many different properties and lend itself to so many different uses? The diversity that we find in all of these products is a reflection of the diversity we find in the structure of the polymer chains. Let's see how that works.

GRAPHIC: Polyethylene
chain structure

NARRATOR:

If we heat ethylene in the presence of certain catalysts, we get a polymer with very long straight chains. Because the chains have few or no branches, they clump together.

Rope, testing polyethylene
products, graphic, trees,
plastic wrap

NARRATOR (NAT SOUND under):

Imagine a rope, many strands together are stronger than a single strand alone. Polyethylene made this way is fairly strong. How strong is this high density polyethylene? The manufacturers have a variety of ways to find out. The polymer can be tested for tensile strength, or impact strength. Here's a test for column crush strength. And these machines test flex strength. This is a test for environmental stress crack resistance. Polymer chains that are even tighter and straighter make for even stronger polyethylene, giving us such materials as very high and ultrahigh density polyethylene. But what about this polyethylene? It's low density polyethylene, much shorter chains, and many branches in each chain. Because of the branches, the chains don't pack together well. Instead of coiled rope, we now have something that looks like tree limbs. (cont.)

NARRATOR cont:

Low density polyethylene is more flexible than its high density cousin, but it's also weaker. It's fine for transporting goldfish, or wrapping fresh produce at the food market. Low density polyethylene feels greasy, it stretches, grows thinner, then pulls apart. Let's see that in the molecular world.

GRAPHIC: Cross-linked polyethylene chains

NARRATOR (MUSIC under):

Under tension, the chains slide, then separate easily. Now, what would happen if we add a catalyst that caused these branches to hook up with other polymer chains? This is called cross-linking, and this third example of polyethylene has a weblike structure. What properties might we expect now?

Hammock, ice rink, soft drink bottles

NARRATOR (NAT SOUND under):

Cross-linked polyethylene acts like a hammock, it's very difficult to tear. Plastic ice is made with cross-linked polyethylene. Soft drink bottle caps are made from cross-linked polyethylene.
(cont.)

NARRATOR cont:

The plastic bottles themselves are made from another polymer, polyethyleneterphthalate, or PET and represent the solution to a formidable challenge, how to create an inexpensive container, able to withstand the gas pressure of several atmospheres. The inventor of the polyethyleneterphthalate soft drink bottle is Nathaniel Wyeth, who comes from the internationally famous family of artists. His brother, Andrew Wyeth, expresses his creativity on canvas, but Nat Wyeth expresses his through chemical engineering.

INTERVIEW: Nathaniel
Wyeth, Inventor, Du Pont
Company

NAT WYETH (SYNC/VO):

I got to thinking about the work that Wallace Caruthers did for Du Pont way back in the days when nylon was born, where he found that, if you took a thread of nylon when it was cold, that is, below the melt point, and stretched it, that it would orient itself. That is, the molecules of the polymer would align themselves.

Pulling polymers

This is what you're doing to the molecules when you orient them, you're lining them up so they can give you the most strength. All, they're all pulling in the direction you want them to pull in.

NARRATOR (NAT SOUND under):
But the bottles kept splitting. Wyeth estimates that he made 10,000 tries and 10,000 failures before he came to make a simple observation.

INTERVIEW: Nathaniel
Wyeth cont.

SUPER: Nathaniel Wyeth,
Inventor, Du Pont Company

NAT WYETH (SYNC/VO):
Well, then I realized what we've got to do now is to align these molecules in the sidewall of the bottle, not only in one direction, but in two directions. So, I thought I'd play a trick on this mold, on this problem. I took two pieces of polyethylene and turned one of them 90 degrees with the other.

Microscopic polyethylene
molecules

So then I had one that would split in this direction, one that would split in that direction. Well, one piece reinforced the other.

INTERVIEW: Nathaniel
Wyeth cont.

As soon as I did that, I could blow bottles. That seems almost dirt simple.
(cont.)

NAT WYETH cont:

But, as I've often said, quoting Einstein, the biggest part of a problem and the easiest way to solving a problem is to understand it, have the problem in a form that you understand what's going on. And what I was doing here was learning about what was going on. Once I knew, it was simple to solve.

Garbage dump, recycling
furnace

NARRATOR (NAT SOUND under):

Someday billions of plastic bottles may grow into mountains of garbage. Some bottles can be recycled, others can be burned as an energy source. But creative minds may find even better solutions to the problem.

INTERVIEW: Nathaniel
Wyeth cont.

NAT WYETH (SYNC/VO):

One of my dreams is that we're gonna be able to melt these bottles, the return bottles, melt them down, mix them with reinforcing fibers, and make car bodies out of them. And that, when the car has served its purpose, rather than put it on a junk pile, melt the car down and make bottles out of it.

DS in lab

DON SHOWALTER (SYNC):

Creative chemistry. We've seen it in action. We've seen how it's possible to make one substance, such as polyethylene, that has a wide variety of properties. But the easiest way to make new polymers is to alter the chemical composition of the beginning monomer. Such changes will radically affect a polymer's characteristics. Let's see what happens when we begin to make simple changes in an ethylene molecule.

GRAPHIC: Molecular structure of styrene and polystyrene

NARRATOR (MUSIC under):

Here's ethylene, just showing the molecular geometry. Let's remove one of the hydrogen atoms and substitute a benzene ring. We have produced a new monomer. This is styrene, a large and bulky molecule compared to ethylene. The polymer of styrene is polystyrene. The benzene rings stick out at random to the left and right. What properties can we expect this material to have in the observable world?

DS in lab

DON SHOWALTER (SYNC):

Think of this cup; it's polystyrene. It's clear and it's light weight. So is this cup, and it's polyethylene. What's the difference? The polyethylene chains are more flexible, so the cup is easily bent. The polystyrene cup shatters, it's brittle, because the polystyrene chains are more rigid.

Insulation

NARRATOR (NAT SOUND under):

Polystyrene makes excellent insulation against heat or cold. Up to 90 percent of this material is air. It's bulky, but it's light weight and easy to work with.

GRAPHIC: Structure of acrylonitrile, close up of fibers

NARRATOR (MUSIC under):

Here's ethylene again. This time we will replace one of the hydrogen atoms with a cyanide group. This is the monomer acrylonitrile. The polymer is polyacrylonitrile, a tough fiber which is woven into clothing and carpets.

DS in lab

DON SHOWALTER (SYNC):

This is polyacrylonitrile. It's much too tough to tear. What's going on here? Why should the addition of a cyanide group make this material so tough?

GRAPHIC

NARRATOR (MUSIC under):

The difference is a result of polarity. The acrylonitrile is more polar than the ethylene unit, so the polymer chains containing cyanide groups are attracted to one another more than the chains with just hydrogen atoms.

Fibers on assembly line,
cutting torch

NARRATOR (NAT SOUND under):

That's why we walk on tough polyacrylonitrile and wrap sandwiches with flexible polyethylene. Acetylene is a highly combustible gas used in cutting torches. Polyacetylene is a solid, with some interesting properties.

GRAPHIC: Molecular
structure of acetylene
and polyacetylene

NARRATOR (MUSIC under):

When we remove two hydrogen atoms from ethylene, we get acetylene, which polymerizes to polyacetylene. When polyacetylene is mixed with certain metal compounds, it conducts electricity. Notice the alternating double bonds. This system of alternating double bonds allows electrons to move freely through the structure, just as electrons move freely through the metal in a piece of wire.

MONTAGE: Polyacetylene
research, computer models,
car assembly line, automobile
research, jet airplanes, space
shuttle launch

NARRATOR (MUSIC and NAT
SOUND under):

This piece of polyacetylene is
completing an electric circuit. When the
polymer is dosed with an iodine
solution, the circuit is completed and the
fan turns. Researchers hope that
polyacetylene may become the battery
material of the future. Perhaps some
day a polyacetylene battery, molded in
the shape of a door panel, will provide
the power for tomorrow's electric car.
The United States consumes more
plastics every year than steel, copper,
and aluminum combined. Some of the
most dramatic applications of polymer
research can be found in automobiles.
It's not only automobiles that benefit
from the revolution in plastics.
Commercial jet airplanes save millions
of dollars per year in fuel costs by using
polymers. And space exploration is
increasingly dependent on synthetic
polymers. For some thoughts on the
direction of polymer research in the 21st
Century, we went to Howard Simmons,
head of research for the Du Pont
Corporation.

INTERVIEW: Howard
Simmons, Vice President,
Du Pont Company

SUPER: Howard E. Simmons,
Vice President, Du Pont
Company

HOWARD SIMMONS (SYNC/VO):

Many places where we use metals today, particularly in structural applications, these will be taken over by polymers in the future. Some of the more exotic things are in the area of medicine, where big markets are forecast in, for example, prosthetics. Right now, today, most artificial bones, joints, ligaments, even arteries, are all made of sophisticated man-made polymers.

Hospital operating room

I just saw a recent market estimate saying that by the 1990s this would be over a two-billion dollar business.

INTERVIEW: Howard
Simmons cont.

A prime reason for this is that polymers allow almost infinite variation in structure, and hence, almost infinite variation in their properties. (cont.)

Chemists at work in a lab

HOWARD SIMMONS cont:

Whereas we now know almost all there is to know about metals and glasses, obviously not everything, but almost, there are almost an infinite variety of polymers that we can conceive so that we can fine tune their structures and fine tune their properties given enough time.

SUPER: THE AGE OF
POLYMERS

MONTAGE: Hospital shots,
construction, car building,
crude oil, program graphics,
polymer products and
properties, chemists at work
in a lab

NARRATOR (MUSIC under):

To review: Polymer science has come a long way in the 20th Century. A hundred years ago we had not yet created our first synthetic polymer. Today we routinely use polymers in medicine, in construction, in transportation. Polymer science begins with breaking crude oil into its component parts through the two processes, fractional distillation and cracking. We make a polymer by stringing together thousands of small molecules, such as the ethylene molecule. This is polymerization. We have shown it taking place in a free radical chain reaction. (cont.)

NARRATOR cont:

The product is the versatile polymer, polyethylene, the most common of the synthetic polymers. These polymers have a wide range of different properties, hard or soft, flexible or brittle, insulators or conductors, depending on the size, structure, and chemical composition of the polymer chains. Polymer chemists continue to alter the structure of molecules or to change the basic building blocks or monomers, to create totally new materials which imitate, even improve on, natural substances.

RH in park

ROALD HOFFMANN (SYNC):

Before we ever began to play in the laboratory, nature made abundant use of polymers in and around us. Why polymers? Well, molecules by themselves have certain properties, but when we string them into chains, when we arrange them into beautiful two- or three-dimensional frameworks, these properties change, the polymers gain strength. Nature made use of polymers because they suited, they suit us. We do well to follow nature's example here in the laboratory. But is there something inherently different about the synthetic polymers that sets them apart from the natural ones? Well, of course there are differences. (cont.)

ROALD HOFFMANN cont:

The differences are there among the synthetic ones. Nylon is different from rayon. They are there among the natural ones. Cotton is different from wool. But more interesting than the differences between the natural and the synthetic ones are the similarities which, in fact, emerge from the molecular level. To see a spider spin her web is hypnotic, it draws us in, it's beautiful. It's also interesting to see how she does it, how her silk glands and spinnerets work. And to me, it is fascinating to go in at the molecular level and to find out how her enzymes make that silk. It is no less beautiful to see a chemist come up with an entirely new process for making polyethylene, and then to watch her implement it at the level of thousands of kilograms an hour pouring out of a factory. The human mind has come up with an ingenious solution to a difficult problem. Human hands, guiding tools, have put it into practice. Surely this, too, is natural and beautiful.

Credits, Closing Montage, Closing Music

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